$ND^{(*)}$ and $NB^{(*)}$ interactions in a chiral quark model

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ND and ND^* interactions become a hot topic after the observation of new charmed hadrons $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$. In this letter, we have preliminary investigated S-wave ND and ND^* interactions with possible quantum numbers in the chiral SU(3) quark model and the extended chiral SU(3) quark model by solving the resonating group method equation. The numerical results show that the interactions between N and D or N and D^* are both attractive, which are mainly from σ exchanges between light quarks. Further bound-state studies indicate the attractions are strong enough to form ND or ND^* molecules, except for $(ND)_{J=3/2}$ and $(ND^*)_{J=3/2}$ in the chiral SU(3) quark model. In consequence ND system with $J = 1/2$ and ND^* system with $J = 3/2$ in the extended SU(3) quark model could correspond to the observed $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$, respectively. Naturally, the same method can be applied to research NB and NB^* interactions, and similar conclusions obtained, i.e. NB and NB^* attractive forces may achieve bound states, except for $(NB^*)_{J=3/2}$ in the chiral SU(3) quark model. Meanwhile, S partial wave phase shifts of $ND^{(*)}$ and $NB^{(*)}$ elastic scattering are illustrated, which are qualitatively consistent with results from bound state problem..

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Years of research works indicate that the chiral SU(3) quark model [1] and the extended chiral SU(3) quark model [2] are successful in studying hadronic systems with light flavors, such as baryon-baryon [1–4], meson-baryon [5–8], meson-meson [9, 10]interactions, structures of multiquark states [11–13], and so on. Recently, the chiral quark model is applied to the heavy flavor sectors, and the tentative works provide interesting results, which include masses of the ground-state baryons [14], the tetraquark states [15–17], interactions of DK [18], $D\bar{D}$ and $B\bar{B}$ [19], $\Sigma_c\bar{D}$ and $\Lambda_c\bar{D}$ [20], and structures of $X(3872)$ [21], $Z_b(10610)$ and $Z_b(10650)$ [22] etc. Inspired by above successes, we are going to investigate other interesting systems with heavy flavors by using the chiral SU(3) quark model and the extended chiral SU(3) quark model, which could provide another effective interpretation for new hadrons with heavy flavors, and test the application of the chiral quark model in the heavy flavor fields.

Belle and Babar Collaborations observed new states $\Sigma_c(2800)$ [23] in 2005 and $\Lambda_c(2940)^+$ [24] in 2007, and subsequently they confirmed their achievements each other[25, 26]. One of the probable explanations of their structures is $\Sigma_c(2800)$ as a ND and $\Lambda_c(2940)^+$ as a ND^* molecular states[27–30]. Then, it is worthwhile to study ND and ND^* interactions dynamically with various methods to further understand the nature of the $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$. In this Letter, we will primarily investigate S-wave ND and ND^* interactions with possible quantum numbers in the chiral SU(3) quark model and the extended chiral SU(3) quark model by solving the resonating group method(RGM) equation. And the same studies are performed to NB and NB^* systems to acquire more information.

The chiral SU(3) quark model and the extended chiral SU(3) quark model have been widely described in the literature [1–8]and we just give their salient features here. The Hamiltonian of the baryon(qqq)-meson($Q\bar{q}$)(q means light quark and Q heavy quark) system can be written as

$$H = \sum_i T_i - T_G + \sum_{i<j} V_{ij} \ , \tag{1}$$

where T_G is the kinetic energy operator for the c.m. motion, and V_{ij} represents the interactions of qq, $Q\bar{q}$, Qq or $q\bar{q}$. For qq or $q\bar{q}$ pair,

$$V_{qq(\bar{q})}(ij) = V^{conf}(ij) + V^{OGE}(ij) + V^{ch}(ij). \tag{2}$$

For Qq or $Q\bar{q}$ pair,

$$V_{Qq(\bar{q})}(ij) = V^{conf}(ij) + V^{OGE}(ij). \tag{3}$$

Note that as a preliminary study, the contributions of $q\bar{q}$ annihilation part and the Goldstone boson exchanges between the heavy-light quark pairs are not considered[14–20].

V^{OGE} is the one-gluon-exchange (OGE) interaction, and the confinement potential V^{conf} is taken as linear form in this work[14–20]. V^{ch} represents the interaction from chiral field coupling, which includes scalar and pseudoscalar boson exchanges in the chiral SU(3) quark model,

$$V^{ch}(ij) = \sum_{a=0}^{8} V_{\sigma_a}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\pi_a}(\boldsymbol{r}_{ij}), \tag{4}$$

and also includes vector boson exchanges in the extended chiral SU(3) quark model,

$$V^{ch}(ij) = \sum_{a=0}^{8} V_{\sigma_a}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\pi_a}(\boldsymbol{r}_{ij}) + \sum_{a=0}^{8} V_{\rho_a}(\boldsymbol{r}_{ij}). \tag{5}$$

Where $\sigma_0, ..., \sigma_8$ are the scalar nonet fields, $\pi_0, .., \pi_8$ the pseudoscalar nonet fields, and $\rho_0, .., \rho_8$ the vector nonet fields.

$V_{q(Q)\bar{q}}$ can be obtained from $V_{q(Q)q}$. For V^{conf} and V^{OGE}, the transformation is given by $\lambda_i^c \cdot \lambda_j^c \to -\lambda_i^c \cdot \lambda_j^{c*}$, while

$$V_{q\bar{q}}^{ch} = \sum_j (-1)^{G_j} V_{qq}^{ch,j}. \quad (6)$$

Here $(-1)^{G_j}$ represents the G parity of the jth meson. The detailed expressions can be found in Refs. [1–8].

TABLE I: Model parameters for the light quarks. The meson masses and the cutoff masses: $m_{\sigma'} = 980$ MeV, $m_\epsilon = 980$ MeV, $m_\pi = 138$ MeV, $m_\eta = 549$ MeV, $m_{\eta'} = 957$ MeV, $m_\rho = 770$ MeV, $m_\omega = 782$ MeV, $m_\phi = 1020$ MeV, and $\Lambda = 1100$ MeV for all mesons.

	χ-SU(3)QM	Ex. χ-SU(3) QM	
	I	II	III
		$f_{chv}/g_{chv} = 0$	$f_{chv}/g_{chv} = 2/3$
b_u (fm)	0.5	0.45	0.45
m_u (MeV)	313	313	313
g_{ch}	2.621	2.621	2.621
g_{chv}	–	2.351	1.973
m_σ (MeV)	595	535	547

The parameters for the light quarks are taken from the previous work [1–4], which can give a satisfactory description of the energies of the baryon ground states, the binding energy of deuteron, the NN scattering phase shifts, and NY cross sections. For simplicity, we only show them as Table I, where the first set is for the chiral SU(3) quark model (I), the second and third sets are for the extended chiral SU(3) quark model by taking f_{chv}/g_{chv} as 0 (II) and 2/3 (III), respectively. Here f_{chv} and g_{chv} are the coupling constants for vector coupling and tensor coupling of the vector meson fields, respectively.

To examine the heavy quark mass dependence, we take several typical values[14, 20] $m_c = 1430$ MeV[15–17], $m_c = 1550$ MeV[31], $m_c = 1870$ MeV[32],$m_b = 4720$ MeV[15–17], $m_b = 5100$[33], $m_b = 5259$ MeV [32]. While our calculated results indicate that the masses of heavy quark (m_Q) contribute little effect, therefore we just take $m_c = 1430$ MeV and $m_b = 4720$ MeV.

The OGE coupling constants and the confinement strengths for light quarks can be determined by fitting the masses of ground-state baryons with light flavors[1–4], whereas those for heavy quarks can be derived from the masses of heavy mesons [14–22]. Our calculations suggest that between the two color-singlet clusters N and $D^{(*)}$ or $B^{(*)}$, there is no OGE interaction and the confinement potential. Therefore these values will not affect the final results and we do not present them here.

With the parameters determined, the S-wave $ND^{(*)}$ and $NB^{(*)}$ systems can be dynamically studied in the framework of the RGM, a well established method for detecting the interaction between two clusters. The details of solving the RGM equation can be found in Refs. [4–10, 34–37]. By solving the RGM equation, one gets the energy of the system, the relative motion wave function, and the elastic scattering phase shifts.

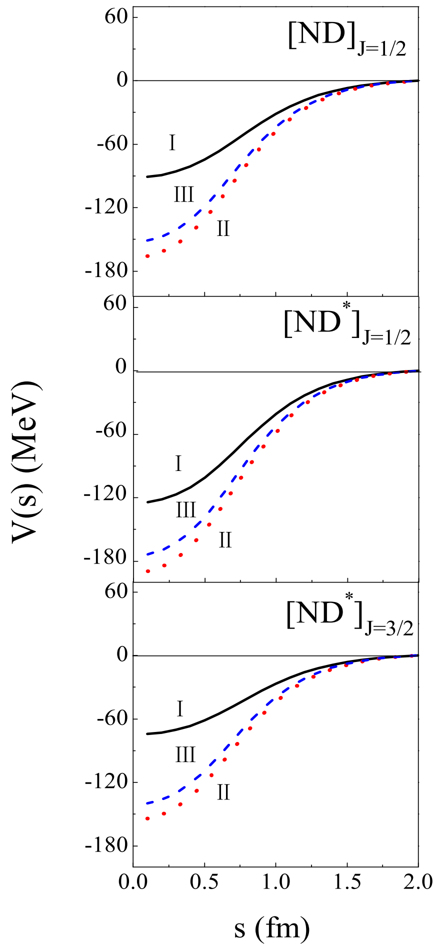

FIG. 1: The GCM matrix elements of the S-wave ND and ND^* total effective potentials as functions of the generator coordinate. The solid line represents the results obtained in chiral SU(3) quark model with set I, and the dotted and dashed lines represent the results in extended chiral SU(3) quark model with set II and set III, respectively.

TABLE II: Binding energies of $ND^{(*)}$ and $NB^{(*)}$.

	χ-SU(3)QM	Ex. χ-SU(3) QM	
	I	II	III
$(ND)_{J=1/2}$		10.0	5.9
$(ND^*)_{J=1/2}$	2.0	18.1	12.8
$(ND^*)_{J=3/2}$		6.6	3.2
$(NB)_{J=1/2}$	1.1	18.2	12.8
$(NB^*)_{J=1/2}$	7.7	28.6	22.0
$(NB^*)_{J=3/2}$		13.7	8.9

Firstly, we consider S-wave ND and ND^* interactions. Fig.1 shows the diagonal matrix elements of the interacion potentials for the $ND^{(*)}$ systems in the generator

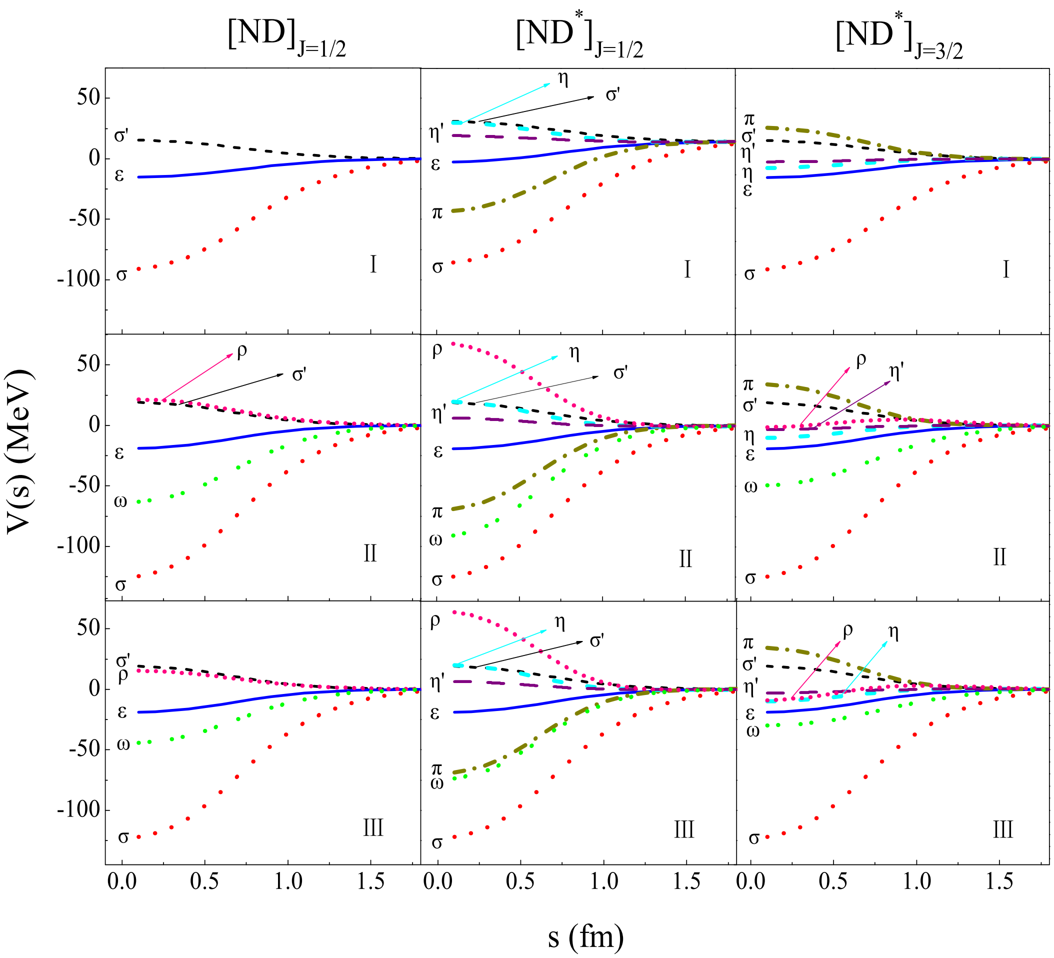

FIG. 2: The GCM matrix elements of the S-wave ND and ND^* effective potentials from bosons exchanges as a function of the generator coordinate.

coordinate method (GCM) [34] calculations, which can be regarded as the effective potentials of two clusters N and $D^{(*)}$. In Fig.1, $V(s)$ denotes the effective potentials between N and $D^{(*)}$, and s denotes the generator coordinate which can qualitatively describe the distance between the two clusters. From the figure, we can see interactions between N and $D^{(*)}$ are attractive, and the attractions in set II are greatest, while those in set I are weakest. Further analysis shows that the attractions dominantly come from σ exchange between light quarks, and others bosons exchanges nearly cancel each other (as shown in Fig.2). And attractions from σ exchanges in set II are strongest.

In order to see whether the $ND^{(*)}$ attractions can result in bound states or not, we have solved the RGM equation for a bound state problem. The corresponding binding energies in three sets of parameters are shown in Table II. One sees except that $(ND)_{J=1/2}$ and $(ND^*)_{J=3/2}$ are unbound in the chiral SU(3) quark model (set I), others can be weak bound states. Obviously, $(ND)_{J=1/2}$ in set II with bing energy 10.0 MeV and III with 10.0 MeV, and $(ND^*)_{J=3/2}$ in set II with 6.6 MeV could correspond to $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$, respectively.

The study of $ND^{(*)}$ elastic scattering processes has also been performed by solving the RGM equation. The calculated S partial wave phase shifts of $ND^{(*)}$ are illustrated in Fig.3 as a function of $ND^{(*)}$ center of mass energy subtracted by the $ND^{(*)}$ threshold energy. We see that the signs of the phase shifts in these two models(three sets of parameters) are the same, and the magnitudes of the phase shifts in the extended chiral SU(3) quark model are higher, especially for set II. This signify that the $ND^{(*)}$ systems get more attractive interactions in the extended chiral SU(3) quark model, which consists with the results of the bind-state calculations (Fig.1 and Table II).

The same research process is applied to $NB^{(*)}$ systems, and similar conclusions are acquired. The binding energies are also listed in Table II, where except

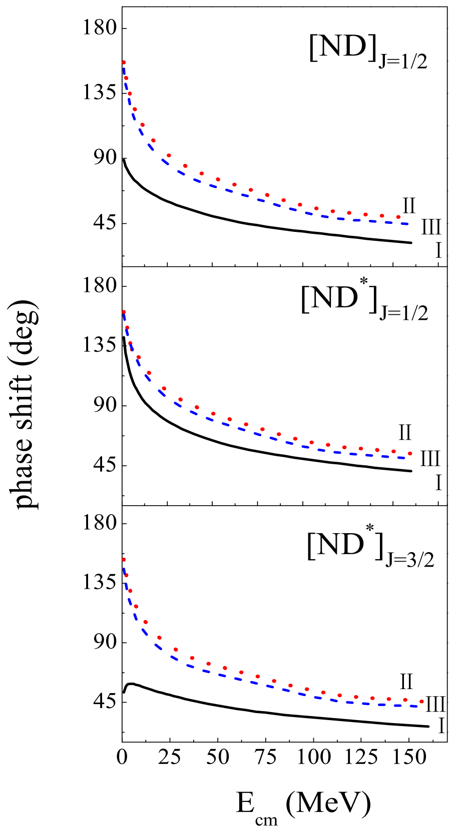

FIG. 3: ND and ND^* S-wave phase shifts as functions of the energy of the center of mass motion. Same notation as in Fig.1

that $(NB^*)_{J=3/2}$ is unbound, others can be weak bound states. Effective interactions between $NB^{(*)}$ are similar to Fig.1 and 2, and S partial wave phase shifts are similar to Fig.3 with all curves move up about $0-10$ degree.

In summary, we have dynamically studied the interactions of S-wave $ND^{(*)}$ and $NB^{(*)}$ system by solving RGM equation in the chiral SU(3) quark model and the extended chiral SU(3) quark model, including bound-state problem and elastic scattering phase shifts. We have obtained some useful information. In our present calculations the potentials between N and $D^{(*)}$ or $B^{(*)}$ two clusters mainly come from σ exchanges, which makes $ND^{(*)}$ and $NB^{(*)}$ interactions are attractive. Furthermore, such attractions are strong enough to form bound states except for $(ND)_{J=1/2}$, $(ND^*)_{J=3/2}$ and $(NB^*)_{J=3/2}$ in the chiral SU(3) quark model(set I). The information extracted from the S partial phase shift of $ND^{(*)}$ and $NB^{(*)}$ is qualitatively consistent with that from bound-state problem. In brief, the observed $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ may be explained as ND molecular state with $J=1/2$ and ND^* molecular state with $J=3/2$, respectively .

Acknowledgments

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